Chapter 3. Introduction to Radiation.

3-1. Atomic Structure.

a. The atom, which has been referred to as the "fundamental building block of matter," is itself composed of three primary particles: the proton, the neutron, and the electron. Protons and neutrons are relatively massive compared to electrons and occupy the dense core of the atom known as the nucleus. Protons are positively charged while neutrons are neutral. The negatively charged electrons are found in a cloud surrounding the nucleus.

b. The number of protons within the nucleus defines the atomic number, designated by the symbol Z. In an electrically neutral atom (that is, one with equal numbers of protons and electrons), Z also indicates the number of electrons within the atom. The number of protons plus neutrons in the nucleus is termed the atomic mass, symbol A.

c. The atomic number of an atom designates its specific elemental identity. For example, an atom with a Z=l is hydrogen, an atom with Z=2 is helium, and Z=3 identifies an atom of lithium. Atoms characterized by a particular atomic number and atomic mass are called nuclides. A specific nuclide is represented by its chemical symbol with the atomic mass in a superscript (for example, ^{3}H, ^{14}C, ^{238}U) or by spelling out the chemical symbol and using a dash to indicate atomic mass (for example, radium-222, uranium-238). Nuclides with the same number of protons (that is, same Z) but different number of neutrons (that is, different A) are called isotopes. Isotopes of a particular element have nearly identical chemical properties, but may have vastly different radiological properties.

3-2. Radioactive Decay.

a. Depending upon the ratio of neutrons to protons within its nucleus, an isotope of a particular element may be stable or unstable. Over time, the nuclei of unstable isotopes spontaneously disintegrate or transform in a process known as radioactive decay or radioactivity. As part of this process, various types of ionizing radiation may be emitted from the nucleus. Nuclides which undergo radioactive decay are called radionuclides. This is a general term as opposed to the term radioisotope which is used to describe an isotopic relationship. For example, ^{3}H, ^{14}C, and ^{125}I are radionuclides. Tritium (^{3}H), on the other hand, is a radioisotope of hydrogen.

b. Many radionuclides such as radium-226, potassium-40, thorium-232 and uranium-238 occur naturally in the environment while others such as phosphorus-32 or sodium-22 are primarily produced in nuclear reactors or particle accelerators. Any material which contains measurable amounts of one or more radionuclides is referred to as a radioactive material. As any handful of soil or plant material will contain some measurable amount of radionuclides, we must distinguish between background radioactive materials and man-made or enhanced concentrations of radioactive materials.

c. Uranium, thorium and their progeny, including radium and radon are Naturally Occurring Radioactive Materials (NORM). Along with an isotope of potassium (K-40) these make up the majority of NORM materials and are found in most all soil and water, and are even found in significant quantities within the human body.

d. Another group of radionuclides are referred to as transuranics. These are merely elements with Z numbers greater than that of uranium (92). All transuranics are radioactive. Transuranics are produced in spent fuel reprocessing facilities and nuclear weapons detonations.

3-3. Activity.

a. The quantity which expresses the degree of radioactivity or radiation producing potential of a given amount of radioactive material is activity. The activity may be considered the rate at which a number of atoms of a material disintegrate, or transform from one isotope to another which is accompanied by the emission of radiation. The most commonly used unit of activity is the curie (Ci) which was originally defined as that amount of any radioactive material which disintegrates at the same rate as one gram of pure radium. That is, 3.7×10^{10} disintegrations per second (dps). A millicurie (mCi) = 3.7×10^{7} dps. A microcurie (µCi) = 3.7×10^{4} dps. A picocurie (pCi) = 3.7×10^{-2} dps.

b. The Systeme Internationale (SI) unit of activity is the becquerel (Bq) which equals 1 dps. Systeme Internationale units, such as meters and grams, are in use throughout the rest of the world. Only the United States still uses units of curies for activity.

c. The activity of a given amount of radioactive material is not directly related to the mass of the material. For example, two one-curie sources containing cesium-137 might

have very different masses, depending upon the relative proportion of non-radioactive atoms present in each source. for example, 1 curie of pure cesium-137 would weigh 87 grams, and 50 billion kilograms (100 million tons) of seawater would contain about 1 curie of Cs-137 from fallout.

3-4. Decay Law.

a. The rate at which a quantity of radioactive material decays is proportional to the number of radioactive atoms present. This can be expressed by the equation (Eq.):

$$N=N_o e^{-\beta t} \qquad \text{Eq. 1}$$

Where N equals the number of atoms present at time t, N_o is the initial number of radioactive atoms present at time 0, β is the decay constant for the radionuclide present, (this can be calculated from the half-life of the material as shown below),and e is the base of the natural logarithms. Table 3-1 indicates half-lives and other characteristics of several common radionuclides.

b. Since activity A is proportional to N, the equation is often expressed as:

$$A = A_o e^{-\beta t} \qquad \text{Eq. 2}$$

Table 3-1. Characteristics of Selected Radionuclides

Radionuclide	Half-life	(Type and max. energy in MeV)
hydrogen-3	12.3 years	β, 0.0186
carbon-14	5370 years	β, 0.155
phosphorus-32	14.3 days	β, 1.71
sulfur-35	87.2 days	β, 0.167
potassium-40	1.3E09 years	β, 1.310
iodine-125	59.7 days	β/X, 0.035
cesium-137	30.2 years	β/X, 0.51/.662
thorium-232	1.4E10 years	β/X, 4.081
uranium-238	4.4E09 years	β/X, 4.147
americium-241	432 years	β/X, 5.49/.059

β-alpha particle, β-beta particle, X-gamma or X-ray

c. Half-life. When half of the radioactive atoms in a given quantity of radioactive material have decayed, the activity is also decreased by half. The time required for the activity of a quantity of a particular radionuclide to decrease to half its original value is called the half-life

($T_{1/2}$) for the radionuclide.

d. It can be shown mathematically that the half-life ($T_{1/2}$) of a particular radionuclide is related to the decay constant (þ) as follows:

$$\frac{\ln 2}{T_{1/2}} \quad \frac{0.693}{T_{1/2}} \qquad \text{Eq. 3}$$

Substituting this value of þ into Equation 2, one gets:

$$A \quad A_o e^{\frac{0.693t}{T_{1/2}}}$$

e. Example 1: You have 5 mCi of phosphorus-32 ($T_{1/2}$ = 14.3 days). How much activity will remain after 10 days?

A = ?

A_o = 5 mCi

t = 10 d

$$\text{þ} = \frac{.693}{14.3\ \text{d}}$$

$A = A_o e^{-\text{þ}t}$

$$A \quad 5 \quad e^{\frac{.693}{14}10}$$

A = 3.1 mCi

f. An alternative method of determining the activity of a radionuclide remaining after a given time is through the use of the equation:

$f = (½)^n$ Eq. 4

where f equals the fraction of the initial activity remaining after time t and n equals the number of half-lives which have elapsed. In Example 1 above,

$n = t/T_{1/2}$

n = 10/14.3

= 0.69

$f = (½)^{0.69}$

= 0.62

$A = fA_o$

= (0.62)(5)

= 3.10 mCi

Both methods may be used to calculate activities at a prior date, that is "t" in the equations may be negative.

g. The activity of any radionuclide is reduced to less than 1% after 7 half-lives and less than 0.1% after 10 half-lives.

3-5. Types of Ionizing Radiation.

a. Ionizing radiation may be electromagnetic or may

consist of high speed subatomic particles of various masses and charges.

(1) Alpha Particles.

Certain radionuclides of high atomic mass (for example,, Ra-226, U-238, Pu-239) decay by the emission of alpha particles. These are tightly bound units of two neutrons and two protons each (a helium nucleus). Emission of an alpha particle results in a decrease of two units of atomic number (Z) and four units of atomic mass (A). Alpha particles are emitted with discrete energies characteristic of the particular transformation from which they originate.

(2) Beta Particles.

A nucleus with a slightly unstable ratio of neutrons to protons may decay by changing a neutron into a proton, or a proton into a neutron through the emission of either a high speed electron or positron called a beta particle. This results in a net change of one unit of atomic number (Z), up one for a beta minus and down one for a beta plus. The beta particles emitted by a specific radionuclide range in energy from near zero to up to a maximum value characteristic of the particular transformation.

(3) Gamma-rays.

(a) A nucleus which has disintegrated is left in an excited state with more energy than it can contain. This excited nucleus may emit one or more photons (that is, particles of electromagnetic radiation) of discrete energies to rid itself of this energy. The emission of these gamma-rays does not alter the number of protons or neutrons in the nucleus but instead has the effect of moving the nucleus from a higher to a lower energy state. Gamma-ray emission frequently follows beta decay, alpha decay, and other nuclear decay processes.

(b) X-rays and gamma-rays are electromagnetic radiation, as is visible light. The frequencies of X- and gamma rays are much higher than that of visible light and so each carries much more energy. Gamma- and X-rays cannot be completely shielded. They can be attenuated by shielding but not stopped completely. A gamma emitting nuclide may yield multiple gamma- and X-rays, each with its own discrete energy. It is possible to identify a gamma emitting nuclide by its spectrum.

(4) X-rays.

X-rays are also part of the electromagnetic spectrum and are indistinguishable from

gamma-rays. The only difference is their source (that is, orbital electrons rather than the nucleus). X-rays are emitted with discrete energies by electrons as they shift orbits and lose energy following certain types of nuclear excitement or decay processes.

(5) Bremsstrahlung radiation.

When a charged particle passes near the nucleus of an atom, it deviates from its original path and is slowed down by the coulombic interaction with the nucleus. When this occurs, the charged particle will emit a photon to balance the energy. These photons are called bremsstrahlung radiation. Bremsstrahlung radiation only becomes a significant source of exposure from high energy beta particles. The amount of bremsstrahlung radiation emitted is proportional to the Z number of the nucleus the beta interacted with, and the energy of the beta particle.

(6) Neutrons.

(a) Neutrons are uncharged particles released during fission of heavy atoms (uranium) or released from some non-radioactive material after bombardment by alpha particles (americium-beryllium [Am-Be] sources). Because neutrons are uncharged particles, they travel further in matter. When neutrons are sufficiently slowed down in matter (thermalized) they are absorbed by matter with an accompanying burst of gamma radiation. The nature of production of the neutron determines whether it is emitted in a spectrum (as in fission) or at a discrete energy (as from Am-Be sources).

(b) A single radioactive decay event may generate a large number of radiations as illustrated in Table 3-2, for example:

Table 3-2
I-125 Radiations

RADIATION	ENERGY(keV)	DECAY%
Gamma	35	6.7
Ka X-ray	27.4	114
Kb X-ray	31	25.6
L X-ray	3.9	12
K Conv. Elec.	3.7	80
L Conv. Elec.	31	11.8
M+ Conv. Elec.	35	2.5
K Auger Elec.	23	20
L Auger Elec.	3-4	160

KeV: kiloelectron volt

3-6. Interaction of Radiation With Matter.

a. Excitation/Ionization.

The various types of radiation (for example, alpha particles,

beta particles, and gamma-rays) impart their energy to matter primarily through excitation and ionization of orbital electrons. The term "excitation" is used to describe an interaction where electrons acquire energy from a passing charged particle but are not removed completely from their atom. Excited electrons may subsequently emit energy in the form of X-rays during the process of returning to a lower energy state. The term "ionization" refers to the complete removal of an electron from an atom following the transfer of energy from a passing charged particle. Any type of radiation having sufficient energy to cause ionization is referred to as ionizing radiation. In describing the intensity of ionization, the term "specific ionization" is often used. This is defined as the number of ion pairs formed per unit path length for a given type of radiation.

b. Characteristics of Different Types of Ionizing Radiation.

(1) Alpha particles have a high specific ionization and a relatively short range. Alpha particles are massive and carry a double positive charge. This combination allows alpha particles to carry a large amount of energy but to easily transfer that energy and be stopped. In air, alpha particles travel only a few centimeters, while in tissue, only fractions of a millimeter. For example, an alpha particle cannot penetrate the dead cell layer of human skin.

(2) Beta particles have a much lower specific ionization than alpha particles and a considerably longer range. The relatively energetic beta's from P-32 have a range of 6 meters in air or 8 millimeters in tissue. The low-energy beta's from H-3, on the other hand, are stopped by only 6 millimeters of air or 5 micrometers of tissue.

(3) Gamma- and X-rays are referred to as indirectly ionizing radiation since, having no charge, they do not directly apply impulses to orbital electrons as do alpha and beta particles. A gamma-ray or X-ray instead proceeds through matter until it undergoes a chance interaction with a particle. If the particle is an electron, it may receive enough energy to be ionized whereupon it causes further ionization by direct interactions with other electrons. The net result is that indirectly ionizing particles liberate directly ionizing particles deep inside a medium, much deeper than the directly ionizing particles could reach from the outside. Because gamma rays and X-rays

undergo only chance encounters with matter, they do not have a finite range. In other words, a given gamma ray has a definite probability of passing through any medium of any depth.

(4) Neutrons are also indirectly ionizing. When striking massive particles such as the nuclei of atoms, the neutron undergoes elastic scattering losing very little energy to the target nucleus. But when a neutron strikes an hydrogen nuclei (a single proton, about the same mass as a neutron) the energy is shared nearly equally between the neutron and the proton resulting in a loss of about half of the neutron's energy before the interaction. The proton now is a charged, directly ionizing particle moving through matter until all of its energy is transferred to the matter.

3-7. Human Health Effects.

The effects of ionizing radiation described at the level of the human organism can be divided broadly into two categories: stochastic (effects that occur by chance) or deterministic (non-stochastic) effects (characterized by a threshold dose below which effects do not occur).

a. Stochastic Effects.

Stochastic effects are those that occur by chance. Stochastic effects caused by ionizing radiation consist primarily of genetic effects and cancer. As the dose to an individual increases, the probability that cancer or a genetic effect will occur also increases. However, at no time, even for high doses, is it certain that cancer or genetic damage will result. Similarly, for stochastic effects, there is no threshold dose below which it is relatively certain that an adverse effect cannot occur. In addition, because stochastic effects can occur in unexposed individuals, one can never be certain that the occurrence of cancer or genetic damage in an exposed individual is due to radiation.

b. Deterministic (Non-Stochastic) Effects.

(1) Unlike stochastic effects, deterministic effects are characterized by a threshold dose below which they do not occur. In addition, the magnitude of the effect is directly proportional to the size of the dose. Furthermore, for deterministic effects, there is a clear causal relationship between radiation exposure and the effect. Examples of deterministic effects include sterility, erythema (skin reddening), and cataract formation. Each of

these effects differs from the other in both its threshold dose and in the time over which this dose must be received to cause the effect (that is acute vs. chronic exposure).

(2) The range of deterministic effects resulting from an acute exposure to radiation is collectively termed "radiation syndrome." This syndrome may be subdivided as follows:

(a) hemopoietic syndrome - characterized by depression or destruction of bone marrow activity with resultant anemia and susceptibility to infection (whole body dose of about 200 rads);

(b) gastrointestinal syndrome - characterized by destruction of the intestinal epithelium with resultant nausea, vomiting, and diarrhea (whole body dose of about 1000 rads); and

(c) central nervous system syndrome - direct damage to nervous system with loss of consciousness within minutes (whole body doses in excess of 2000 rads).

(3) The LD_{50} (that is, dose that would cause death in half of the exposed population) for acute whole body exposure to radiation in humans is about 450 rads.

3-8. Determinants of Dose.

The effect of ionizing radiation upon humans or other organisms is directly dependent upon the size of the dose received and the rate at which the dose is received (for example, 100 mrem in an hour versus 100 mrem in a year). The dose, in turn, is dependent upon a number of factors including the strength of the source, the distance from the source to the affected tissue, and the time over which the tissue is irradiated. The manner in which these factors operate to determine the dose from a given exposure differs significantly for exposures which are "external" (that is, resulting from a radiation source located outside the body) and those which are "internal" (that is, resulting from a radiation source located within the body).

a. External Exposures.

(1) Exposure to sources of radiation located outside the body are of concern primarily for sources emitting gamma-rays, X-rays, or high energy beta particles. External exposures from radioactive sources which emit alpha or beta particles with energies less than 70 keV are not significant since these radiations do not penetrate the dead outer cell layer of the skin.

(2) As with all radiation exposures, the size of the dose resulting from an external exposure is a function of:

(a) the strength of the source;

(b) the distance from the source to the tissue being irradiated; and

(c) the duration of the exposure.

In contrast to the situation for internal exposures, however, these factors can be altered (either intentionally or inadvertently) for a particular external exposure situation, changing the dose received.

(3) The effectiveness of a given dose of external radiation in causing biological damage is dependent upon the portion of the body irradiated. For example, because of differences in the radiosensitivity of constituent tissues, the hand is far less likely to suffer biological damage from a given dose of radiation than are the gonads. Similarly, a given dose to the whole body has a greater potential for causing adverse health effects than does the same dose to only a portion of the body.

b. Internal Exposures.

(1) Exposure to ionizing radiation from sources located within the body are of concern for sources emitting any and all types of ionizing radiation. Of particular concern are internally emitted alpha particles which cause significant damage to tissue when depositing their energy along highly localized paths.

(2) In contrast to the situation for external exposures, the source-to-tissue distance, exposure duration, and source strength cannot be altered for internal radiation sources. Instead, once a quantity of radioactive material is taken up by the body (for example, by inhalation, ingestion, or absorption) an individual is "committed" to the dose which will result from the quantities of the particular radionuclide(s) involved. Some medical treatments are available to increase excretion rates of certain radionuclides in some circumstances and thereby reduce the committed effective dose equivalent.

(3) In general, radionuclides taken up by the body do not distribute equally throughout the body's tissues. Often, a radionuclide concentrates in an organ. For example, I-131 and I-125, both isotopes of iodine, concentrate in the thyroid, radium and plutonium in the bone, and

uranium in the kidney.

(4) The dose committed to a particular organ or portion of the body depends, in part, upon the time over which these areas of the body are irradiated by the radionuclide. This, in turn, is determined by the radionuclide's physical and biological half-lives (that is, the effective half-life). The biological half-life of a radionuclide is defined as the time required for one half of a given amount of radionuclide to be removed from the body by normal biological turnover (in urine, feces, sweat).

3-9. Background Radiation.

a. All individuals are continuously exposed to ionizing radiation from various natural sources. These sources include cosmic radiation and naturally occurring radionuclides within the environment and within the human body. The radiation levels resulting from natural sources are collectively referred to as "natural background". Naturally occurring radioactive material (NORM) can be detected in virtually everything. Natural potassium contains about 0.01% potassium-40, a powerful beta emitter with an associated gamma ray. Uranium, thorium and their associated decay products, which are also radioactive, are common trace elements found in soils throughout the world. Natural background and the associated dose it imparts varies considerably from one location to another in the U.S. and ranges from 5 to 80 microroentgens per hour. It is estimated that the average total effective dose equivalent from natural background in the U.S. is about 250 mrem/person/year. This dose equivalent is composed of about 166 mrem/person/year from radon, 34 mrem/person/year from natural radioactive material within the body, 25 mrem/person/year from cosmic radiation, and 25 mrem/person/year from terrestrial radiation.

b. The primary source of man-made non-occupational exposures is medical irradiation, particularly diagnostic procedures (for example, X-ray and nuclear medicine examinations). Such procedures, on average, contribute an additional 100 mrem/person/year in the U.S. All other sources of man-made, non-occupational exposures such as nuclear weapons fallout, nuclear power plant operations, and the use of radiation sources in industry and universities contribute an average of less than one mrem/person/year in the U.S.

3-10. Radiation Quantities.

a. Exposure (roentgen).

Exposure is a measure of the strength of a radiation field at some point. It is usually defined as the amount of charge (that is, sum of all ions of one sign) produced in a unit mass of air when the interacting photons are completely absorbed in that mass. The most commonly used unit of exposure is the roentgen (R) which is defined as that amount of X or gamma radiation which produces 2.58E-4 coulombs per kilogram (C/kg) of dry air. In cases where exposure is to be expressed as a rate, the unit would be roentgens per hour (R/hr) or more commonly, milliroentgen per hour (mR/hr). A roentgen refers only to the ability of PHOTONS to ionize AIR. Roentgens are very limited in their use. They apply only to photons, only in air, and only with an energy under 3 mega-electron-volts (MeV). Because of their limited use, no new unit in the SI system has been chosen to replace it.

b. Absorbed Dose (rad).

Whereas exposure is defined for air, the absorbed dose is the amount of energy imparted by radiation to a given mass of any material. The most common unit of absorbed dose is the rad (Radiation Absorbed Dose) which is defined as a dose of 0.01 joule per kilogram of the material in question. One common conversion factor is from roentgens (in air) to rads in tissue. An exposure of 1 R typically gives an absorbed dose of 0.97 rad to tissue. Absorbed dose may also be expressed as a rate with units of rad/hr or millirad/hr. The SI unit of absorbed dose is the gray (Gy) which is equal to 1 joule/kg which is equal to 100 rads.

c. Dose Equivalent (rem).

(1) Although the biological effects of radiation are dependent upon the absorbed dose, some types of particles produce greater effects than others for the same amount of energy imparted. For example, for equal absorbed doses, alpha particles may be 20 times as damaging as beta particles. In order to account for these variations when describing human health risk from radiation exposure, the quantity, dose equivalent, is used. This is the absorbed dose multiplied by certain "quality" and "modifying" factors (Q) indicative of the relative biological-damage potential of the particular type of radiation. The unit of dose equivalent is the rem (Radiation Equivalent in Man) or, more commonly, millirem. For beta, gamma- or X-ray exposures, the numerical value

of the rem is essentially equal to that of the rad. The SI Unit of dose equivalent is the sievert (Sv) which is equal to: 1 Gy X Q; where Q is the quality factor. Q values are listed in Table 3-3 (Note that there is quite a bit of discrepancy between different agency's values).

Table 3-3
Q Values

Radiation Type	NRC	ICRU	NCRP
X & Gamma Rays	1	1	1
Beta Particles (Except ^{3}H)	1	1	1
Tritium Betas	1	2	1
Thermal Neutrons	2	-	5
Fast Neutrons	10	25	20
Alpha particles	20	25	20

(2) Example: An individual working at a Corps lab with I-125 measures the exposure at a work station as 2 mR/hr. The NRC licenses and regulates the lab. What is the dose equivalent to a person sitting at the work station for six hours?

DE = Exposure x 0.97 rad/R x Q

Exposure = Exposure Rate x Time

Q for gamma-radiation = 1

DE = Rate x Time x 0.97 x Q

DE = 2 mR/hr x 6 hr X 0.97 rad/R x 1 = 11.64 mrem.

d. Deep Dose Equivalent (DDE).

(1) The DDE is the dose to the whole body tissue at 1 centimeter (cm) beneath the skin surface from external radiation. The DDE can be considered to be the contribution to the total effective dose equivalent (TEDE) from external radiation.

(2) Example: A worker is exposed to 2 R of penetrating gamma radiation. What is his/her DDE?

DDE = exposure x 0.97 rad/R x Q
Q for gamma radiation = 1
DDE = 2 R x 0.97 rad/R x 1 = 1.94 rem.

e. Effective Dose Equivalent (EDE).

(1) Multiplying the dose equivalent by a weighting factor that relates to the radiosensitivity of each organ and summing these weighted dose equivalents produces the effective dose equivalent. Weighting Factors are shown in Table 3-4. The EDE is used in dosimetry to account for different organs having different sensitivities to radiation.

Table 3-4
Weighting Factors

Gonads	0.25
Breast	0.15
Lung	0.12
Thyroid	0.03

Bone	0.03
Marrow	0.12
Remainder	0.30

(2) Example: A person is exposed to 3 mR/hr of gamma-radiation to the whole body for six hours. What is the effective dose equivalent to each organ and to the whole body?

EDE = þ (DE x WF)
DE = R x Q
R = Rate x Time
Q for gamma = 1
R = 3 mR/hr x 6 hrs. = 18 mR
18 mR x 0.97 mrad/mR = 17 mrad
DE = 17 mrad x 1 = 17 mrem
EDE for:
Gonads = 17 mrem x 0.25 = 4.25 mrem
Breast = 17 mrem x 0.15 = 2.55 mrem
Lung = 17 mrem x 0.12 = 2.04 mrem
Thyroid = 17 mrem x 0.03 = 0.51 mrem
Bone = 17 mrem x 0.03 = 0.51 mrem
Marrow = 17 mrem x 0.12 = 2.04 mrem
Remainder = 17 mrem x 0.30 = 5.10 mrem

EDE for whole body: 17 mrem.
(note that the weighting factor for the whole body is one)

f. Committed Dose Equivalent (CDE).

(1) The CDE is the dose equivalent to organs from the intake of a radionuclide over the 50-year period following the intake. Radioactive material inside the body will act according to its chemical form and be deposited in the body, emitting radiation over the entire time they are in the body. For purposes of dose recording, the entire dose equivalent organs will receive over the 50-years following the intake of the radionuclides is assigned to the individual during the year that the radionuclide intake took place. The CDE is usually derived from a table or computer program, as the value is dependent upon the radionuclide, its chemical form, the distribution of that chemical within the body, the mass of the organs and the biological clearance time for the chemical. Two common databases are MIRD and DOSEFACT that contain CDEs for various radionuclides. The CDE can be calculated from the data in 10 CFR 20 Appendix B, or from the EPA Federal Guidance Report #11 if there is only one target organ, otherwise the dose must be calculated from the contribution of the radionuclide in every organ to the organ of interest.

(2) Example: An individual ingests 40 microcuries of I-131. What is the CDE? Because the dose to the thyroid from iodine-131 is 100 times greater than the dose to any other organ we can assume that the

thyroid is the only organ receiving a significant dose and can use the 10 CFR 20 approach, from 10 CFR 20, Appendix B. The non-stochastic (deterministic) Annual Limit of Intake (ALI) is 30 µCi. A non-stochastic ALI is the activity of a radionuclide that, if ingested or inhaled, will give the organ a committed dose equivalent of 50 rem.
DE/ALI x 50 rem = committed dose equivalent to the organ.
40 µCi/30 µCi x 50 rem = 67 rem.

(3) An example of the CDE derived from a table is presented in Table 3-5 for inhalation of Co-60.

g. Committed Effective Dose Equivalent (CEDE).

(1) Multiplying the committed dose equivalent by a weighting factor that relates to the radiosensitivity of each organ and summing these weighted dose equivalents produces the committed effective dose equivalent. The CEDE can be considered to be the contribution from internal radionuclides to the TEDE.

(2) Example: A male worker inhales 10 µCi Co-60. What is his CEDE?

Using the CDE above for Co-60, and the weighting factors above, we get the following:
EDE for:

Gonads = 10 µCi x 6.29E+00 mrem/µCi x 0.25 =
15.73 mrem

Table 3-5
Inhalation Coefficients ($H_{50,T}$) in mrem/µCi

Co-60 ($T_{½}$ = 5.271 year) Class Y F1 = 5.0E-02 AMAD = 1.0 µm

organ	($H_{50,T}$)	organ	($H_{50,T}$)
Adrenals	1.11E+02	Lungs	1.27E+03
Bladder Wall	1.09E+01	Ovaries	1.76E+01
Bone surface	4.99E+01	Pancreas	1.17E+02
Breast	6.80E+01	Red Marrow	6.36E+01
Stomach Wall	1.01E+02	Skin	3.77E+01
Small Intestine	2.60E+01	Spleen	9.99E+01
Up lg Intestine	3.59E+01	Testes	6.29E+00
Lw lg intestine	2.93E+01	Thymus	2.12E+02
Kidneys	5.77E+01	Thyroid	5.99E+01
Liver	1.23E+02	Uterus	1.70E+01

$H_{rem,50}$ = 1.33E+02 $H_{E,50}$ = 2.19E+02
ICRP 30 ALI = 30 µCi

Breast= 10 µCi x 6.80E+01 mrem/µCi x 0.15 = 102.00 mrem

Lung = 10 µCi x 1.27E+03 mrem/µCi x 0.12 = 1524.00 mrem

Thyroid= 10 µCi x 5.99E+01 mrem/µCi x 0.03 = 17.97 mrem

Bone = 10 µCi x 4.99E+01 mrem/µCi x 0.03 = 14.97 mrem

Marrow = 10 µCi x 6.36E+01 mrem/µCi x 0.12 = 76.32 mrem

Remainder = 10 µCi x 1.33E+02 mrem/µCi x 0.30 = 399.00 mrem

CEDE for whole body: 2149 mrem

h. Total Effective Dose Equivalent (TEDE).

(1) The sum of the DDE and the CEDE. Dose from internal radiation is no different from dose from external radiation. Regulations are designed to limit TEDE to the whole body to 5 rem per year, and to limit the sum of the DDE and the CDE to any one organ to 50 rem per year.

(2) Example: The person working in example d. also inhales 10 µCi Co-60 as in example g. What is his or her TEDE?

TEDE = DDE + CEDE
From Example d his DDE is 1.74 rem = 1,740.00 mrem
From example g his CEDE is 2,149.00 mrem

TEDE 3,889.00 mrem

3-11. Biological Effects of Ionizing Radiation.

Biological effects of radiation have been studied at different levels; the effects on cells, the effects on tissues (groups of cells), the effects on organisms, and the effects on humans. Some of the major points are reviewed below.

a. Cellular Effects.

(1) The energy deposited by ionizing radiation as it interacts with matter may result in the breaking of chemical bonds. If the irradiated matter is living tissue, such chemical changes may result in altered structure or function of constituent cells.

(2) Because the cell is composed mostly of water, less than 20% of the energy deposited by ionizing radiation is absorbed directly by macromolecules (for example, Deoxyribonucleic Acid (DNA). More than 80% of the energy deposited in the cell is absorbed by water molecules where it may form highly reactive free radicals.

(3) These radicals and their products (for example, hydrogen peroxide) may initiate numerous chemical reactions which can result in damage to macromolecules and/or corresponding damage to cells. Damage produced within a cell by the radiation induced formation of free radicals is described as being by indirect action of radiation.

(4) The cell nucleus is the major site of radiation damage leading to cell death. This is due to the importance of the DNA within the nucleus in controlling all cellular function. Damage to the DNA molecule may prevent it from providing the proper template for the production of additional DNA or Ribonucleic Acid (RNA). In general, it has been found that cell radiosensitivity is directly proportional to reproductive capacity and inversely proportional to the degree of cell differentiation. Table 3-6 presents a list of cells which generally follow this principle.

Table 3-6. List of Cells in Order of Decreasing Radiosensitivity

Very radiosensitive	Moderately radiosensitive	Relatively radioresistant
Vegetative intermitotic cells, mature lymphocytes, erythroblasts and spermatogonia, basal cells, endothelial cells.	Blood vessels and interconnective tissue, osteoblasts, granulocytes and osteocytes, sperm erythrocytes.	Fixed postmitotic cells, fibrocytes, chondrocytes, muscle and nerve cells.

(5) The considerable variation in the radiosensitivities of various tissues is due, in part, to the differences in the sensitivities of the cells that compose the tissues. Also important in determining tissue sensitivity are such factors as the state of nourishment of the cells, interactions between various cell types within the tissue, and the ability of the tissue to repair itself.

(6) The relatively high radiosensitivity of tissues consisting of undifferentiated, rapidly dividing cells suggest that, at the level of the human organism, a greater potential exists for damage to the fetus or young child than to an adult for a given dose. This has, in fact, been observed in the form of increased birth defects following irradiation of the fetus and an increased incidence of certain cancers in

individuals who were irradiated as children.

3-12. Ways to Minimize Exposure.

a. There are three factors used to minimize external exposure to radiation; time, distance, and shielding. Projects involving the use of radioactive material or radiation generating devices need to be designed so as to minimize exposure to external radiation, and accomplish the project. A proper balance of ways to minimize exposure and the needs of the project need to be considered from the earliest design stages. For example, if a lead apron protects a worker from the radiation, but slows him or her down so that it requires three times as many hours to complete the job, the exposure is not minimized. Additionally, placing a worker in full protective equipment and subjecting the worker to the accompanying physical stresses to prevent a total exposure of a few millirems does not serve the needs of the project or of the worker.

(1) Time.

Dose is directly proportional to the time a individual is exposed to the radiation. Less time of exposure means less dose. Time spent around a source of radiation can be minimized by good design, planning the operation, performing dry-runs to practice the operation, and contentious work practices.

(2) Distance.

Dose is inversely proportional to the distance from the radiation source. The further away, the less dose received. Dose is related to distance by the equation:

$$I_2 \quad I_1\left(\frac{D_1}{D_2}\right)^2$$

Where:
I_1 = Intensity at Distance 1,
D_1 = Distance 1,
I_2 = Intensity at Distance 2,
D_2 = Distance 2.

Doubling the distance from a source will quarter the dose (see Figure 3-1).

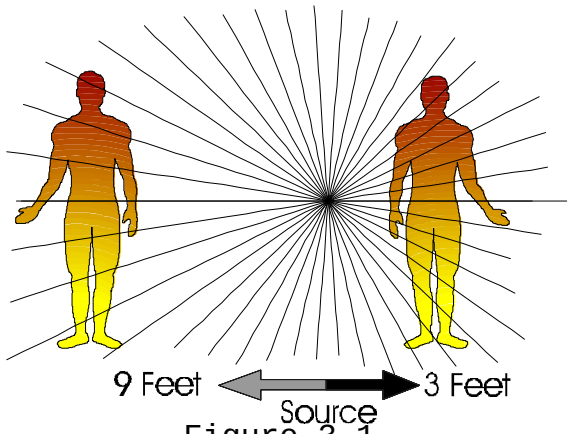

Figure 3-1.

Distance from a radiation source can be maximized by good

design, planning the operation, using extended handling tools or remote handling tools as necessary, and by conscienscious work practices.

(3) Shielding

(a) Dose can be reduced by the use of shielding. Virtually any material will shield against radiation but its shielding effectiveness depends on many factors. These factors include material density, material thickness and type, the radiation energy, and the geometry of the radiation being shielded. Consult a qualified expert to determine shielding requirements. Cost considerations often come into play. The shielding provided by a few centimeters of lead may be equaled by the shielding provided by a few inches of concrete, and the price may be lower for the concrete. Table 3-7 lists half-value layers for several materials at different gamma ray energies.

(b) Shielding can be used to reduce dose by placing radiation sources in shields when not in use, placing shielding between the source and yourself, good design of the operation, and contentious work practices.

Table 3-7
Half-value layers (cm) for gamma rays

E_β (MeV)	Lead	Concrete	Water	Iron	Air
0.1	0.4	3.0	7.0	0.3	3622
0.5	0.7	7.0	15.0	1.6	6175
1.0	1.2	8.5	17.0	2.0	8428
1.5	1.3	10.0	18.5	2.2	10389

b. Personnel Protective Equipment (PPE).

PPE is a last resort method for radiation exposure control. When engineering controls using time, distance, shielding, dust suppression, or contamination control cannot adequately lower the exposure to ionizing radiation or radioactive material, PPE may be used. PPE may include such items as:

(1) full-face, air-purifying respirators (APRs) with appropriate cartridges;

(2) self-contained breathing apparatus (SCBA);

(3) supplied air; and

(4) shielded gloves, aprons, and other clothing.

c. Selection of PPE is based on unique conditions at each job site. The PPE may be required in the following circumstances:

(1) when handling contaminated materials with removable contamination;

(2) when working in contamination, high contamination, and Airborne Radioactivity Areas; or

(3) when required by an NRC license or ARA.

d. Specific PPE requirements for each job site should be obtained from USACE or a USACE contractor HP or industrial hygienist. Respirator use must meet the requirements of 29 CFR 1910 or 1926 and USACE respiratory protection requirements of EM 385-1-1. The respiratory protection factors for different types of respirators are listed in 10 CFR 20, Appendix A.

NOTE Half-face APRs will not be used for any USACE work involving radioactive material, unless there is no other practical solution. Any special use of half-face APRs will first be approved by the RPO.

e. Cartridges for radionuclides must be selected with consideration for the radionuclide's chemical form. Respirator filters approved for use under 30 CFR 11 may still be used until July 1998. By that time, all respirator cartridges must be classified according to the new National Institute of Occupational Safety and Health (NIOSH) modular approach described in 42 CFR 84. With the new modular approach to respirator certification, cartridges approved by NIOSH, will no longer be labeled for dusts/mists/fumes/radioactive dusts. The color coding has also changed. Dust/mist/fume filters will now be labeled as N95, N99, N100, R95, R99, R100, P95, P99, and P100. The number relates to the filtering efficiency, and the letter relates to the type of aerosol, with P100 being the most protective over the widest range of aerosol types. Dust/mist and dust/mist/fume cartridges do not provide any protection against radioactive vapors or radioactive noble gases. Consider the use of combination cartridges to control dust and vapors, and activated charcoal cartridges to control noble gasses. When selecting APRs, consider the buildup of radioactive material in the cartridges. A high concentration of gamma radiation-emitting particles or vapor in cartridges may produce

a radiation field positioned very close to the face and chest of the person wearing the APR.

f. Any PPE will slow down the working speed of personnel, and extend the time needed for entry and exit. The increase in dose due to the increased time in the radiation field must be weighed against the radiation dose reduction caused by the use of PPE. The use of whole body personal protective equipment, particularly the impermeable type can cause heat stress problems. A heat stress monitoring program shall be implemented to evaluate and control heat stress hazards whenever PPE is used.

3-13. Standing Operating Procedures.

Where a project or operation uses radiation in a method that is amenable to written standing operating procedures (SOPs), the RPO overseeing the operations shall assist in the preparation of SOPs. Most manufacturers of instruments and articles containing radioactive material or that generate ionizing radiation, include SOPs in their operating manuals. The RPO shall review these SOPs and ensure that they meet USACE safety guidelines outlined in this manual and the requirements of ER 385-1-80 and EM 385-1-1 before use.

3-14. Monitoring and Surveying Equipment.

a. Anytime personnel are working with radioactive material or radiation generating devices, radiation monitoring procedures will be used. Equipment needs to be selected that can detect the radiation or radiations in question. Table 3-8 is a general guide to types of detectors and the range and types of radiations they detect. Some radiations are extremely difficult to detect in the field. Weak beta emitters such as tritium (maximum beta energy of 18.6 kilo-electron volts (keV) and weak gamma emitters such as iodine-125 present monitoring problems. Prior to work involving radioactive materials, consult the RPO and HP to select appropriate instruments and procedures for the detection and quantification of the specific radiation in question.

b. Radiation Monitoring Instruments.

(1) Gas-filled Detectors.

Gas-filled detectors consist of a gas-filled chamber with a voltage applied such that a central wire becomes the anode and the chamber wall the cathode. Any ion pairs produced by radiation interacting with the chamber

move to the electrodes where they are collected to form an electronic pulse which can be measured and quantified. Depending upon the voltage applied to the chamber, the detector may be considered an ionization chamber, a proportional counter or a Geiger-Muller (GM) detector.

(a) An ionization chamber is a gas-filled chamber containing an anode and a cathode. As radiation passes through the gas it ionizes some of the gas molecules. These ion pairs are attracted to the anode and cathode and create an electrical pulse. The pulses are counted and integrated and displayed on the meter face in roentgens per hour. Because of its design, an ionization chamber has a very linear response to radiations of different energies. For this reason, an ionization chamber is the preferred instrument for quantifying personnel external radiation exposures.

(b) Because of its versatility and dependability, the GM detector is the most widely used portable survey instrument. A GM detector with a thin window can detect alpha, beta and gamma radiation. It is particularly sensitive to medium-to-high energy beta particles (for example, as from P-32) and X-and gamma-rays as well. The GM detector is fairly insensitive to low energy X or gamma rays; that is below 50 keV, to low energy beta particles such as those emitted by S-35 and C-14, and cannot detect the weak betas from H-3 at all. Unlike the ionization chamber, the GM detector does not actually "measure" exposure rate. It instead "detects" the number of particles interacting in its sensitive volume per unit time. The GM should thus read-out in counts per minute (cpm) although it can be calibrated to approximate mR/hr for certain situations. With these advantages and limitations a Geiger-Muller detector on a rugged survey meter is the instrument of choice for initial entry and survey of radiation sources and radioactive contamination in the field.

(2) Scintillation Detectors.

(a) Scintillation detectors are based upon the use of various phosphors (or scintillators) which emit light in proportion to the quantity and energy of the radiation they absorb. The light flashes are converted to photo electrons which are multiplied in a series of diodes (that is, a photomultiplier) to produce a large electrical pulse. Because the light output and resultant electrical pulse from a scintillator is proportional to the amount of energy

deposited by the radiation, scintillators are useful in identifying the amount of specific radionuclides present (that is, scintillation spectrometry).

(b) Portable scintillation detectors are widely used for conducting various types of radiation surveys. Of particular use to workers working with low energy gamma radiation, as from radioiodine, is the thin crystal sodium iodide (NaI) detector which is capable of detecting the emissions from I-125 with efficiencies nearing 20% (a GM detector is less than 1% efficient for I-125).

c. Assaying Instruments.

(1) The most common means of quantifying the presence of beta-emitting radionuclides is through the use of liquid scintillation counting. In these systems, the sample and phosphor are combined in a solvent within the counting vial. The vial is then lowered into a well between two photomultiplier tubes for counting.

(2) Solid scintillation detectors are particularly useful in identifying and quantifying gamma-emitting radionuclides. The common gamma well-counter employs a large (for example, 2" x 2" or 3" x 3") crystal of NaI within a lead shielded well. The sample vial is lowered directly into a hollow chamber within the crystal for counting. Such systems are extremely sensitive but do not have the resolution of more recently developed semiconductor counting systems, such as high-purity germanium detectors.

d. Neutron detectors, sometimes called 'neutron balls' or 'rem balls' are used for detection of neutrons. Neutron detectors use a hydrogenous moderator to slow down the neutrons which will allow the neutrons to interact with charged particles. These charged particles then are detected using a conventional radiation detector. Boron trifluoride (BF_3) is a common detector gas used for neutron detection.

e. Semiconductor diode detectors or solid state

Table 3-8
Radiation Detection Instruments

Detector type	Radiation Detected	Detection Limit	Comments
GM-thick walled	þ >50 keV	100 dpm	Limited use.
GM-thin window	ß >35 keV þ >35 keV	100 dpm	Good for detecting contamination, not good for quantifying.

Detector type	Radiation Detected	Detection Limit	Comments
NaI- 2" x 2" crystal	þ >50 keV	500 dpm	Good for detection and quantification.
NaI-thin crystal	ß >50 keV þ >25 keV	500 dpm	Good for detecting low-energy gamma radiation.
Ionization Chamber	ß >50 keV þ >50 keV	0.2 mR/hr	Most accurate for exposure measurement.
Pressurized Ionization Chamber	þ >50 keV	.01 mR/hr	Good for environmental surveys.
Micro R meter	þ >50 keV	.01 mR/hr	Good for environmental surveys.
HPGe	þ >40 keV	variable	Lab equipment, can quantify trace amounts. Field models available.
Liquid Scintillation	þ, ß, þ	variable	Lab equipment, can quantify trace amounts. Field models available.
Gas Proportional	þ, ß, þ	variable	Lab equipment, can quantify trace amounts field models available.

detectors use a solid material with a charge applied to it to detect the energy deposited by radiation. These detectors can be designed to provide good detection of most all radiation, but particular types of radiation and energy ranges, each call for a different configuration.

f. One type of solid state detector that is finding widespread use is the high purity germanium detector (HPGe). The HPGe, like its predecessor the germanium-lithium (GE(Li)) detector, has excellent energy resolution and is commonly used in laboratories for identification and quantification of gamma emitting radionuclides. A primary drawback of the HPGe detector is the requirement to supercool the detector. This

is done by attaching a Dewar flask containing liquid nitrogen to the detector. HPGe systems are being made that are field portable, using small Dewar flasks and laptop computers, and can provide laboratory quality analysis in the field.

g. Energy proportional detectors such as scintillation detectors, semiconductor diode detectors and HPGe detectors are often coupled with a multi-channel analyzer (MCA) to allow for determination of the energy of the radiation detected, and through reference, to determine the radioisotope that emitted the radiation and the quantity of that isotope in the sample measured. Most modern MCAs are used in conjunction with computers which process the information, contain the library of radionuclides referenced by energy of radiation, and display software for digital and graphic output.

h. Instrument Calibration.

(1) Radiation survey meters are calibrated with a radioactive source and an electronic pulser. When an electronic calibration is performed, the instrument is checked for response to a radioactive source. In most situations, survey meters must be calibrated at least annually and after servicing. (Battery changes are not considered "servicing".)

(2) Survey meters will be function tested with a check source or other dedicated source before each use. If the survey meter is not responding properly, it may not be used for surveys until it is repaired. There is no need to keep a record of the function checks, but a record must be kept of the discovery of the improper response and the service of the meter to correct the problem, as well as of the recalibration of the meter.

I. Quality Control.

Quality control of instrumentation is essential in a radiation protection program. All instruments used for monitoring safety and health should be subjected to a quality control (QC) program. Two tracking/trending methods are commonly used in instrument QC. The general principle is applicable to both field and lab instruments. The two methods are background trending and check source trending.

(1) Background trending is done by plotting the daily background reading versus days since last calibration. Background trending can indicate when instrument probes become contaminated, by showing a rise in the background rate. Care must be taken in measuring the background daily to assure

that the instrument is in approximately the same location and that the location is contaminant free.

(2) Check-source tracking is a method of assuring that the instrument is responding properly, and remaining in calibration. Check-source tracking is performed by plotting a daily check source reading of a dedicated check source against the days since calibration. Check-source tracking can indicate damage to the instrument or probe, variance of the electronics or changes in the meter response. Figure 3-2 is an example of background tracking and check-source tracking.

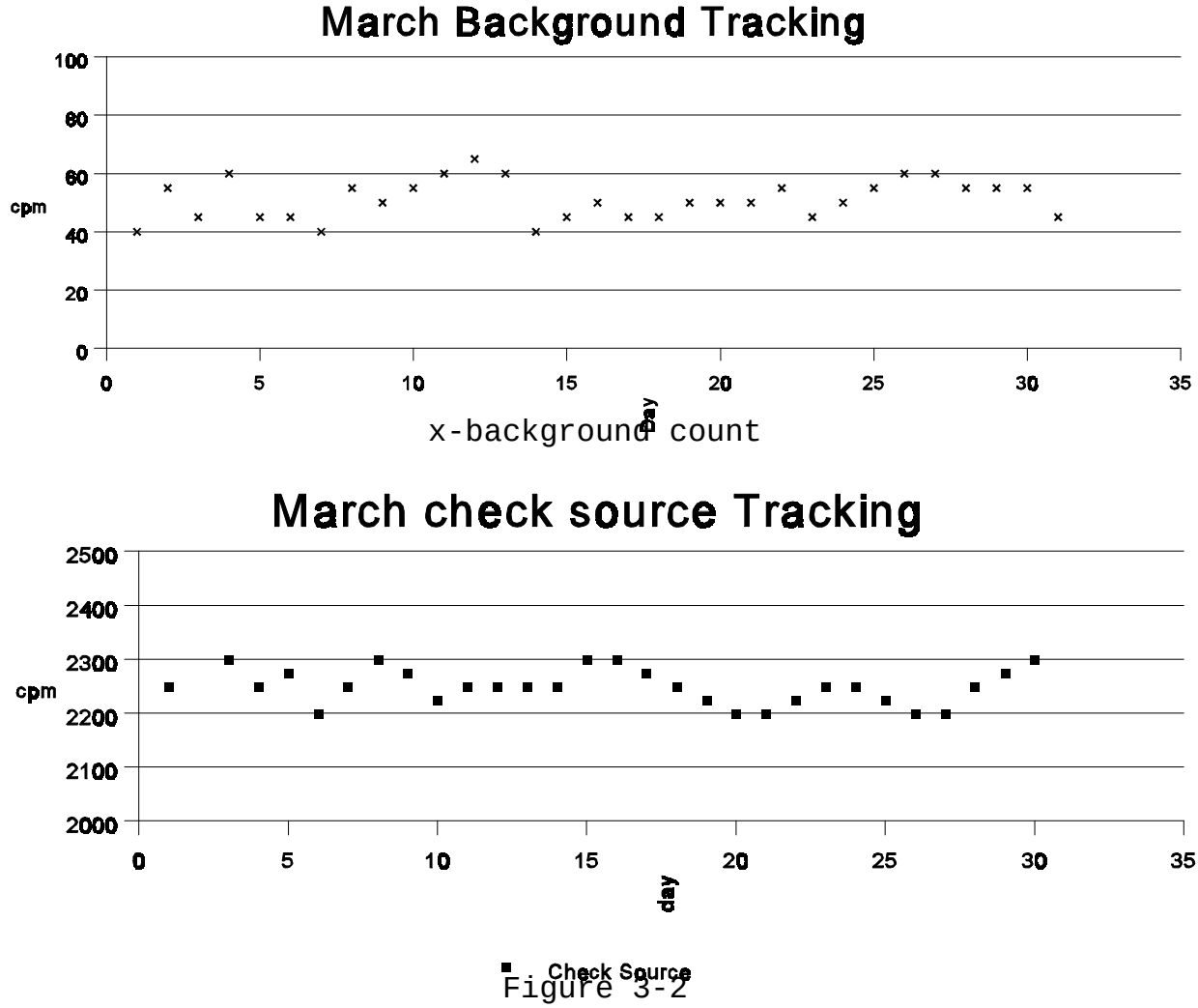

Figure 3-2